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EDM machining capabilities of magnesium (Mg) alloy WE43 for medical applications

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Abstract

Besides high geometrical accuracy medical devices strongly require a good surface integrity of the produced parts. Surfaces should be optimized to reduce friction or to increase cell adhesion for optimal fitting, mechanical stability and biocompatibility to reduce the risk of inflammatory reactions. Therefore surfaces should posses tailored roughness, a closed structure without pores and cracks and should not contain any toxic substances as a result of the machining process. New biomaterials like magnesium alloys for biodegradable orthopaedic implants are very difficult to machine with conventional processes especially for complex and filigree 3D-structures. Therefore, alternative manufacturing technologies are desired and need to be developed. This paper analyzes the capabilities of state-of-the-art EDM process technologies regarding achievable surface integrity.

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Keywords: Surface integrity, EDM, Magnesium

Introduction

Similar to the aerospace industry, medical applications are very complex and highly demanding for the used materials. Besides the functionality of the implant the used materials need to be highly biocompatible and need to achieve a high fatigue life. The human body is naturally a highly corrosive environment and the replacement of implants should be prevented whenever possible. Unscheduled surgeries increase the risk of complications, are always painful for the patient and are accompanied with additional recreation periods. To avoid surgeries it is also necessary to prevent any inflammatory reaction of the surrounding tissue of the implant. Besides the natural characteristics of the used materials the production process and the resulting surface integrity in particular has a significant influence on the biocompatibility as well as the fatigue life of the implant. Therefore surfaces should posses a tailored roughness, closed structure without pores and cracks and should not contain any toxic substances as a result of the machining process.

Newest implant generations offer a large variety of enhanced functionalities due to superior material properties and the use of filigree 3D microstructures. Magnesium for example is one of the most promising materials to be used for biodegradable orthopaedic implants [1]. These temporary implants take advantage of the corrosive environment of the human body which absorbs the implant. Due to the natural regenerative capacities of the human body new natural bone tissue grows into the space formerly occupied by the implant. A second surgery for the removal of temporary

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implants or permanent implants with defects can therefore be avoided. No foreign material is left in the body which improves the quality of life significantly for patients.

Nevertheless filigree 3D-microstructures needed by newest implant generations are very difficult to machine with conventional processes Therefore, alternative manufacturing technologies are desired and need to be developed. This paper analyses the capabilities of state-of-the-art EDM process technologies regarding achievable dimensional accuracy and surface integrity.

Due to the removal principle of EDM the hardness of a material is not relevant and is not directly linked to the tool wear, since there is hardly any direct contact between tool and workpiece during a stable EDM process [2]. This also leads to the fact that there is only a very low process force affecting the workpiece. Therefore EDM has also become a very common manufacturing process for miniaturized components in micro engineering and medical applications[3].

Taking this into account, it is reasonable to discuss the capabilities of Electro Discharge Machining of new biomaterials which are relatively unknown to this unconventional machining process to widen the structural possibilities of medical applications. This includes the achievable geometrical accuracy for microstructures and corresponding economic efficiency but most of all its influence on the biocompatibility. Therefore the surface integrity, which has the main influence on the bio-response of the surrounding tissue and also the functionality of the implant, are the focus of this paper.

High process temperatures can change the microstructure of the zone near the surface and therefore modify the material properties. Spontaneous heating and cooling of the material can lead to tensile stress in the surface which are the cause for cracks and may decrease the fatigue strength of the implant. The process must therefore be optimized to reduce the heat affected zone as much as possible.

1. EDM Principles

It is known that the thermal removal principle of EDM affects the surface of the machined workpiece as well as the area near the surface in a similar fashion as the heat generated during other conventional processes like grinding. Due to short electrical discharges between the tool electrode and the workpiece usually occurring at the shortest distance between them, small parts of material are melted and removed creating small craters on the surface. This is repeated until the desired shape is reached as a negative form of the electrode. Craters form the surface of the machined part and their size determines the surface roughness. The depth of the craters is directly linked to the energy and duration of the discharge as well as the resulting temperature and therefore the depth of the heat affected zone. This leads to the conclusion that the parameters of the EDM generator which provides the energy for the discharges are the main influencing factors on the depth and degree of the heat effected zone [4][5].

To minimize the heat affected zone EDM technologies with low discharge energies are desirable. By decreasing discharge energies the craters are smaller since the material removal of every discharge decreases and thus the surface roughness decreases as well. Furthermore the gap width between tool electrode and workpiece becomes smaller and the geometrical accuracy increases.

But this also means that the material removal rate decreases which is directly linked to the economic efficiency of the production process. Therefore it is necessary to perform a first machining process with high discharge energies and a high material removal rate with a following process step to reduce the heat affected zone, improve geometrical accuracy and surface quality. This can either be performed by a different machining technology, or which should be the desired choice by repeated EDM processes and sequentially reducing the discharge energies. The goal is to reduce the heat affected zone until it cannot be detected anymore or it verifiably has no effect on the application. In this course the potential of EDM in terms of micro machining can be fully exploited.

By investigating the best parameter combination for a certain application it is possible to achieve the desired surface topology and thus receive a tailored surface for the medical application.

2. EDM process development of unconventional materials

Due to the fact that magnesium is not a typical material for EDM a number of fundamental and characteristic parameters for an effective EDM process need to be determined. With these parameters it is possible to optimize the machining result in terms of the desired surface properties and realize an effective EDM process window. A usual procedure is to start the parameter optimization using a standard steel technology. Therefore a standard steel workpiece material ASP 23 (DIN: S6-5-3) is used as reference material. The composition of both materials is listed in Table 1 and an excerpt of the physical parameters which are important for the EDM process are shown in Table 2.

Table 1 Composition of WE43 and ASP 23[6][7]

Material						
WE43	Yttrium 3.7-4.3 %	Rare E. 2.4-4.4 %	Zirconium 0.4 %			Balance Mg
ASP 23	Tungsten 6.40 %	Molybdenum 5.00 %	Chromium 4.20 %	Vanadium 3.10 %	Carbon 1.30 %	Balance Fe

A Sodick AQ537L wire EDM machine tool with deionized water as dielectric fluid was used for all experiments in this paper. A brass wire with a diameter of 0.25 mm was used as tool electrode. The parameters of the machining technology can only be used for a relative comparison since they are company specific parameters and do not necessarily represent physical parameters. Therefore a state-of-the-art technology for the machining of steels was chosen for a main cut and the following 5 trim cuts.

Table 2 Excerpt of physical parameters of WE43 and Asp 23[6][7]

	Density	Thermal conductivity	Modulus of elasticity	Melting range	Vickers hardness
WE43	1840 kg / m^3	51.3 W/m K	44 GPa	540-640 °C	85-105
ASP 23	8000 kg / m^3	24 W/m K	230 GPa	>1200 °C	800

To achieve high geometrical accuracies it is necessary to determine the exact gap widths for every cut of the two materials. For this purpose test cuts were performed for each cut independently and the wire clearance was determined using light microscopy. The results up to the 4th trim cut are listed in Fig. 1a. The energies for the 5th trim cut were too small for an exact measurement. Due to the sequential decreasing discharge energies with every trim cut the wire clearance decreases as well. The gap width of WE43 is larger than the reference material. This corresponds to the lower melting temperature and higher thermal conductivity of the magnesium alloy. During every discharge more material is removed because deeper material layers reach higher temperatures and lower temperatures are sufficient for material removal respectively.

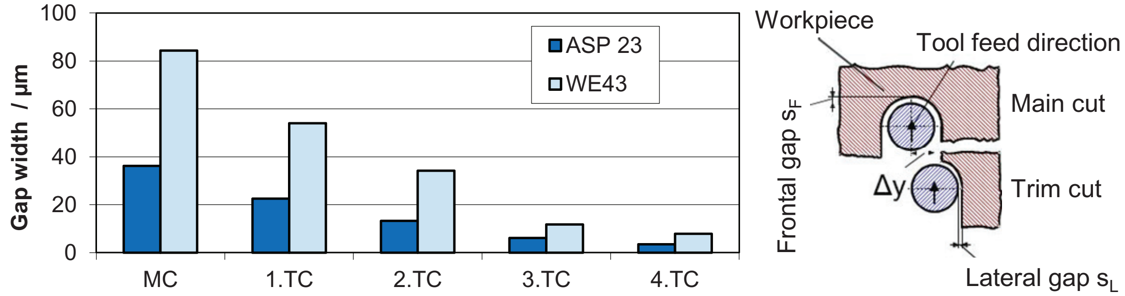

Fig. 1 Gap width of WE43 in comparison to ASP 23 (a) and schematic drawing of tool path correction of trim cuts (b) [4]

With higher discharge energies the difference is more significant. Based on these results the correction of the wire path Δy can be calculated in order to receive the desired wire path, as seen in Fig. 1b. Goal is to reduce the heat affected zone and overall roughness with every cut in such a way that the machining time is minimized while creating an optimal surface quality. The correction of the path was performed based on the reference technology for steel.

Table 3 Achievable cutting rates for the used materials with standard steel technologies

	Cutting rate / mm^2/min
WE43	up to 369
ASP 23	up to 40

To measure the achievable cutting rate several test cuts were performed in both materials. The lengths of the cuts were 10 mm and the height of the test sample was 30 mm. The results for the used standard technologies for steel are shown in Table 3. These results are sufficient for a relative comparison under the given conditions of the machine tool.

Due to the lower melting temperature and higher thermal conductivity more material of the magnesium alloy can be removed in the same time. But this cannot explain the large divergence of the cutting rates. In this case it is very likely that there are completely different material removal mechanisms during the machining of magnesium compared to the machining of steel (e.g. oxidization). Therefore further investigations are needed to determine if these results are in fact generated by different material removal mechanisms and why they lead to a higher cutting rate for the machining of magnesium.

3. Investigation of surfaces created by EDM

Using the determined corrections of the cutting path a similar surface roughness as with the reference material can be achieved, as shown in Fig. 2. The Ra values of WE43 are generally bigger than the one for the reference material. This fact corresponds very well to the observed large gap width of the material. In conclusion it can be seen that although the roughness of WE43 is generally larger than that for the reference material a similar surface roughness Ra significantly smaller than 1 µm can be achieved for both materials.

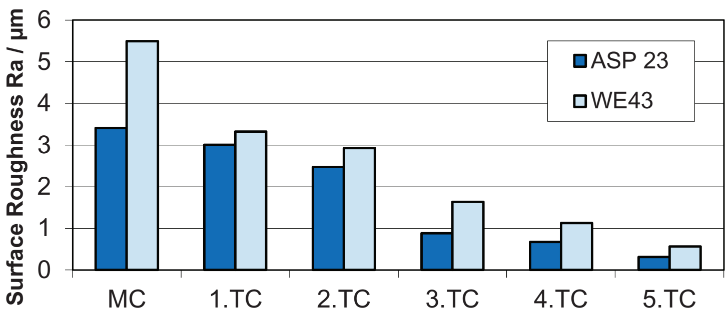

Fig. 2 Comparison of the achieved surface roughness in comparison to the reference steel material

To investigate the resulting surface integrity of the machined materials SEM images were taken of the surface and the surface near zone after creating cross sections of the test samples. Using this method the characteristics of the heat affected zone due to the machining process can be made visible. These are possible pores, cracks, recast material of the workpiece and the tool electrode as well as the white layer formation in particular. These characteristics can be used to predict the performance of the material and its surface.

In the SEM image of the main cut an affected surface area of up to 20 µm can be observed, as seen in Fig. 3a. In the formation of the white layer a large pore as well as a long crack are visible which is typical for the solidification of material which was melted but not removed. A difference between a recast layer and white layer cannot be identified clearly.

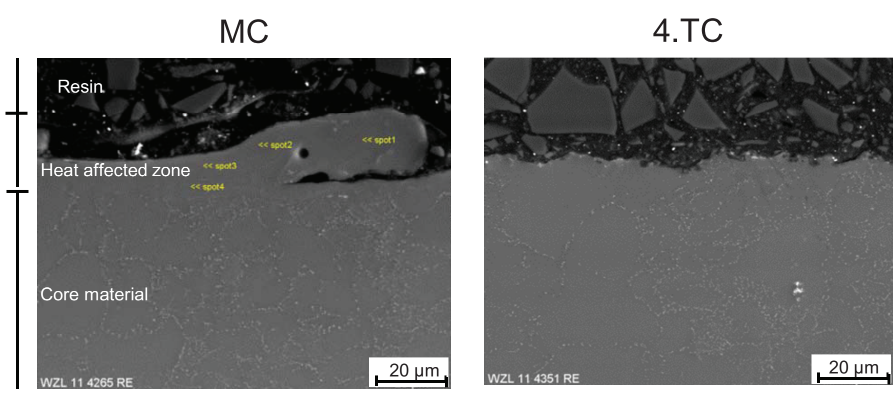

Fig. 3 SEM images of cross sections of the WE43 samples (a) main cut (b) 4^{th} trim cut with a magnification of 1000 x

An additional local Energy-dispersive X-ray spectroscopy (EDX) analyses of the base material and the recast layer stresses the fact that no tool electrode material can be found in the near surface area. Only Magnesium and Yttrium could be identified which corresponds to the composition of WE43. No copper or zinc was found which would indicate recast material of the brass wire. In case of using the part as an implant an inflammatory reaction due to foreign material is therefore unlikely. In the course of the trim cuts the affected layer is sequentially reduced. Already in the 4th trim cut a recast layer or white layer can hardly be seen at all.

SEM image and EDX analysis of the surface in the top view (Fig. 4) show only very little recast material of the tool electrode similar to the cross sections. Only very small particles of the tool material could be found which makes an inflammatory reaction unlikely but further investigations are necessary on this matter. The images show a waved surface with large hollow spaces which are the result of flowing melted material that solidifies on the surface again. Several large pores can be observed in the main cut as well as the 4th trim cut. In contrast to the main cut the surface of the last trim cut show signs of small cracks. These cracks are caused by the thermal expansion of the material and the resulting thermal shock stress possibly because the cooled down material cannot flow back to its origin.

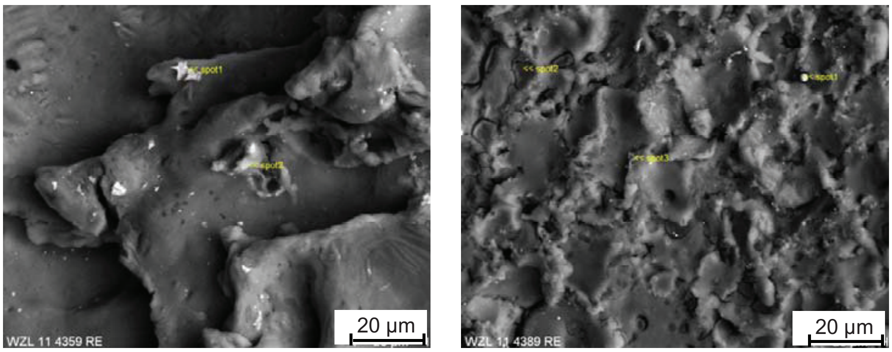

Fig. 4 SEM image of the surface (a) main cut and (b) 4th trim cut

4. Examples for geometries achieved with state-of-the-art steel technologies in WE43 with adapted offsets

Using the altered correction of the cutting path rectangular bar geometries were created. As quality criteria the thickness of the machined bars at the top and bottom were used. The thickness of the bars were varied from 0.5 mm to 0.01 mm with a constant height of 1 mm. As seen in Fig. 5 a thickness of down to approximately 60 µm can be realized using the standard technology. Under this barrier the bars tend to bend and the thickness at the tips decreases compared to the thickness at the bottom. A programmed thickness of 100 µm as seen in Fig. 5a was created with a deviation lower than 5%.

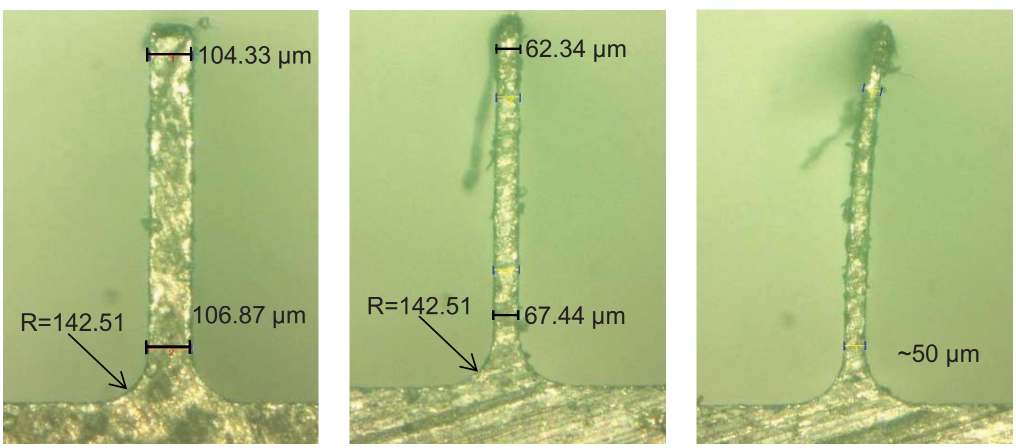

Fig. 5 Light microscopy investigation on the geometrical accuracy of rectangular geometries (a) 100 µm (b) 60 µm and (c) 50 µm

An example for the achievable aspect ratios of the machining of WE43 by EDM is given in Fig. 6. The aspect ratio was increased from 2:1 up to 40:1 without noticeable geometrical deviation. The thickness of the bar geometry was

0.5 mm for every cut. Further testing is needed for the investigation of the fatigue strength and barriers of these filigree structures.

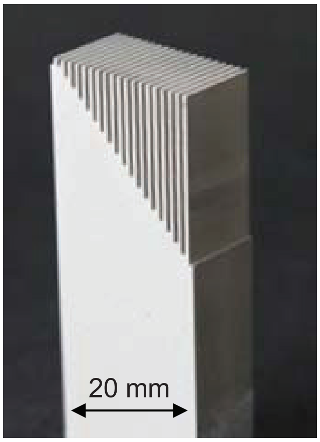

Fig. 6 Example for EDM machining of WE43 with aspect ratio of up to 40:1

5. Conclusion

Wire Electro Discharge Machining is capable of machining magnesium alloys efficiently and with good surface integrity. By adapting the tool path correction of state-of-the-art EDM technologies for the machining of steel alloys very good results were achieved. By using trim cut technologies the white layer formation could be reduced significantly. The SEM images showed hardly any white layer after the 4^{th} trim cut and no foreign material could be detected in the cross section. Similar images of the direct surface showed only small isolated particles of foreign material. An EDX analysis identified these particles as material of the tool electrode. Due to the very high material removal rate in comparison to the reference steel material an economic and efficient manufacturing process is very likely, especially since the used technology was not extensively optimized until now. This fact is also true in terms of geometrical accuracy. As seen in the test geometries good results can be achieved with standard steel technologies.

In conclusion EDM is capable of machining the biomaterial magnesium efficiently without damaging the surface layer in a significant manner using trim cuts and up to date generator technology. But further investigations are needed to determine the dominant material removal mechanism during the machining of magnesium to identify relevant process parameters for a material specific optimization. Analysis of the generated debris and a comparison with the machining of other materials with similar cutting rates, e.g. aluminum, will give more insight into the electro discharge machining of magnesium. In-vivo and in-vitro testing will give proof of the capabilities of EDM in terms of biocompatibility for medical applications in the future.

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